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Procedia Engineering 81 (2014) 921 – 926

**Procedia
Engineering**www.elsevier.com/locate/procedia

11th International Conference on Technology of Plasticity, ICTP 2014, 19-24 October 2014,
Nagoya Congress Center, Nagoya, Japan

Deformation-induced martensitic transformation and workhardening of type 304 stainless steel sheet during draw-bending

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Abstract

Deformation-induced martensitic transformation and workhardening behavior in draw bending process was investigated, on a Type 304 stainless steel sheet, in comparison with that in uniaxial tension experiment. The Vickers hardness of the draw-bent sheet at the surface is much larger than that at the mid-plane, and it becomes remarkably larger with increasing blank holder force. The significant increase of hardness in the deformed sheet is due to α' -martensitic transformation. The volume fraction of α' -martensite in the draw-bent sheet is smaller than that in the uniaxially pulled sheet with the same plastic strain. In uniaxial tension the sheet is plastically deformed in one direction monotonically, but in contrast, in draw-bending tension-to-compression (i.e., bending-to-unbending) deformation takes place when the sheet is drawn over the die-corner. The difference in the evolution of the martensite between draw-bending and uniaxial tension is explained from such a difference in deformation mode.

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Selection and peer-review under responsibility of the Department of Materials Science and Engineering, Nagoya University

Keywords: Stainless steel; Draw bending; Martensitic transformation; Workhardening; Deformation microstructure

1. Introduction

Austenitic stainless steels are widely used in many fields of industry because of their excellent mechanical and functional properties, such as high ductility and high strength, as well as excellent corrosion and heat resistances.

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Type 304 steel, which is the most popular austenitic stainless steel, exhibits extremely large elongation of over 50% in uniaxial tension (Fukase et al., 1968) owing to its severe workhardening nature that comes from the deformation induced α' -martensitic transformation (Tamura et al., 1969). However, when using such a hard sheet metal for press forming operation, we may encounter some difficulties, such as large springback (Ohashi, et al. 1977) and die galling (Hayashi, 1997). In addition, the risk of delayed cracking in deep-drawn cups becomes higher with increasing α' -martensite volume in the formed products (Sumitomo, et al., 1976).

Therefore, in order to predict the formability of type 304 stainless steel sheet, it is of vital importance to have a model describing the evolution of α' -martensitic phase. A model of the kinetics for the deformation-induced martensitic transformation was first proposed by Olson et al. (1975), and later the strain rate effect was considered in the model by Stringfellow et al. (1992). In these models the volume fraction of the transformation-induced martensite is expressed as a function of accumulated plastic strain. However, there are some articles reporting that the evolution of the martensite is not only a unique function of plastic strain but it is also dependent on deformation mode. Hamasaki et al. (2014), recently found that the martensitic phase transformation behavior under cyclic deformation is not the same as one under uniaxial tension.

Accordingly, in the present study, the martensitic transformation behavior of type 304 stainless steel sheets during draw-bending process, where a sheet is subjected to bending-unbending when the sheet is drawn over the die corner, is investigated. The Vickers hardness distributions along the sheet thickness were determined for drawn sheets for several levels of BHF. The volume fractions of α' -martensite were measured both at the surface and the mid-plane of the drawn sheet for various BHFs, and they were compared to those obtained from uniaxially pulled specimens. From these, the effect of stress reversal on the martensitic transformation is discussed.

2. Experimental procedure

2.1. Specimen

Type 304 stainless steel sheet of 1 mm thick (as annealed) was used for the experiment.

2.2. Draw-bending

The experimental set-up for draw-bending and the specimen is schematically illustrated in Fig. 1. The draw-bending experiments were conducted for three levels of blank holder force (BHF), 10, 30 and 5 kN. The specimen was drawn over the die-corner (die-corner radius was 3 mm) at a punch speed of 0.167 mm/s up to 40 mm punch travel, where a lubricant with high viscosity (Johnson wax #122) was applied on the die and blank holder surfaces.

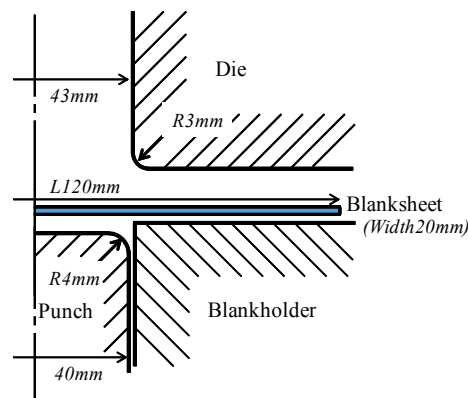


Fig. 1. Experimental set-up and specimen for draw-bending.

2.3. Evaluation of materials completed testing

The volume fraction of the deformation-induced martensite at the surface of the specimen was measured using a ferrite meter (MP-30, Fischer co. ltd.). For an accurate determination of the volume fraction of the martensite phase, thus measured volume fraction of the martensite had been calibrated using the X-ray analysis.

In the analysis of α' -martensitic transformation behavior in the thickness direction, separation of the ferritic phase from the austenitic phase was performed by the Electron beam Backscatter Diffraction (EBSD) method using a field emission-type scanning electron microscope (JSM-7000F FE-SEM, JEOL co. ltd.).

Furthermore, hardness distributions in the sheet, both in the longitudinal and thickness directions, were determined by the micro-Vickers hardness measurement (HV0.1), as schematically illustrated in Fig. 2. In the longitudinal direction, the hardness at the mid-point of the sheet was measured throughout the side-wall of the draw-bent sheet (from the flange to the punch-corner) with an interval of 1 mm. In the sheet thickness direction, the measurement was conducted at a position of 10 mm away from the end of die-corner with an interval of 100 μm in the thickness direction from the surface to the mid-plane of the sheet.

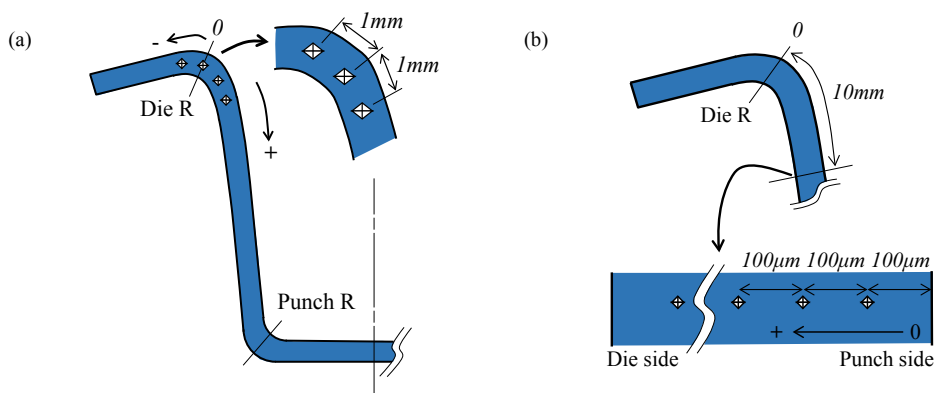


Fig. 2. Locations for micro-Vickers hardness measurement: (a) in longitudinal direction; (b) in thickness direction.

3. Results and discussion

3.1. Workhardening of draw-bent sheets

The specimens after draw-bending experiments are shown in Fig. 3, where we can see that the side-wall curl decreases significantly with increasing BHF since it gives a tensile load to the sheet. The hardness distributions of draw-bent sheets are summarized in Figs 4(a) and (b), where (a) shows the hardness at the mid-plane, and (b) the result in the thickness direction, for three different BHFs, 10, 30 and 50 kN. In draw-bending, the sheet is subjected to bending strain together with stretching strain. From these figures, it is clear that the overall workhardening increases with increasing BHF because of a larger stretching strain. Under a low BHF (see Fig. 4(b) for BHF=10 kN), the bending strain is dominant compared to the stretching strain, thus the hardness values at the sheet surfaces are much larger than that at the mid plane. In contrast, under a large BHF (see Fig. 4(b) for BHF=50 kN), the difference in hardness between at the surface and at the mid-plane is not so large, since a large stretching strain is induced by the BHF.

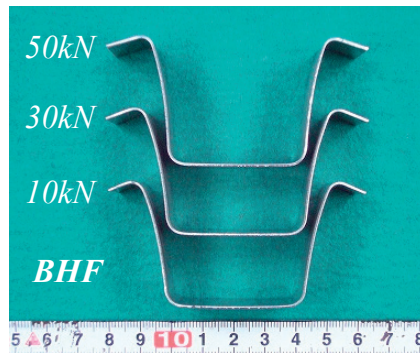


Fig. 3. Specimens after draw-bending experiments.

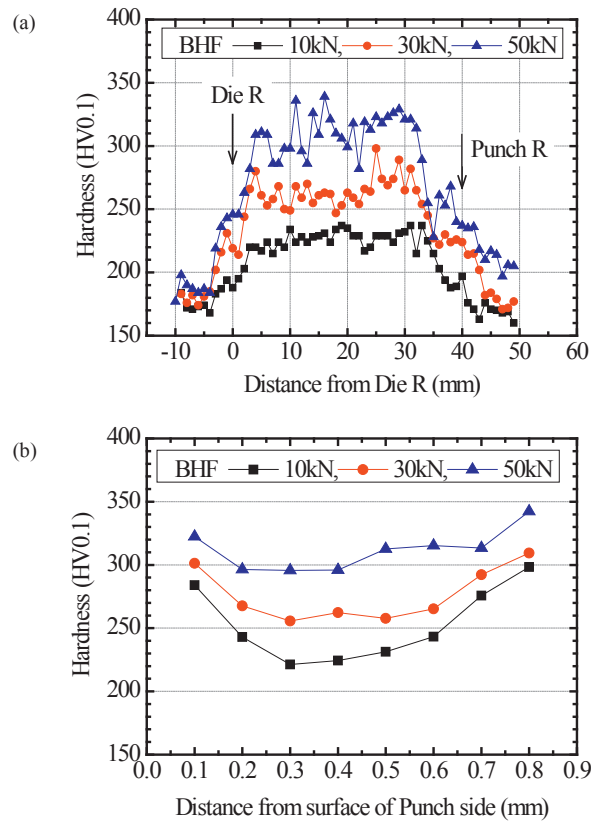


Fig. 4. Hardness distributions in draw-bent sheets: (a) in longitudinal direction (measured at mid-plane); (b) in the thickness direction (measured at 10mm away from end of die corner).

3.2. Relationship between volume fraction of martensite and the hardness

The volume fractions of α' -martensite were measured with either the ferrite meter or the EBSD analysis. EBSD images for the draw-bent sheets, at both the punch-side surface and the mid-plane, tested under BHF=10, 30 and 50 kN, are shown in Fig. 5. The result for the uniaxially pulled specimen, at 22% tensile strain, is also shown in the figure. The difference in appearance of the martensitic phase between at the sheet surface and at the mid-plane is

not so obvious for BHF=50 kN, compared to the case of BHF=10 kN, which is corresponding to the aforementioned result of hardness distribution. The relationship between volume fraction of the martensite and the Vickers hardness in the draw-bent sheets, together with the result in the uniaxially pulled specimen, is shown in Fig. 5, where the hardness is found to be expressed as a unique function of the volume fraction of martensite. From this, it would be concluded that the major mechanism of workhardening of type 304 stainless steel is the evolution of martensite during plastic deformation.

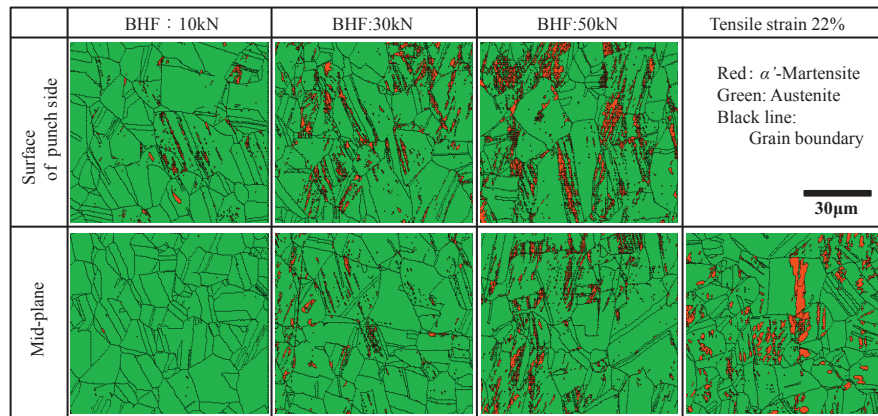


Fig. 5. The EBSD analysis on deformation-induced transformation of the samples after draw-bending and tensile test.

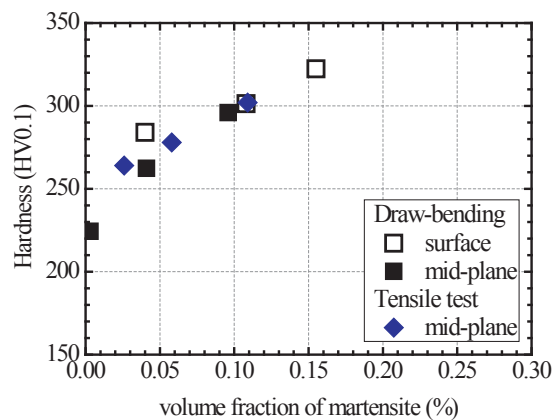


Fig. 6. Relationship between volume fraction of α' -martensite and the Vickers hardness.

3.3. Effect of bending-unbending on martensitic transformation

Based on the kinetics for the deformation-induced martensitic transformation Olson et al. (1975) and Stringfellow et al. (1992) presumed that the volume fraction of α' -martensite is given as a unique function of accumulated plastic strain (i.e. effective plastic strain). To verify this hypothesis, the effective plastic strain of the draw-bent sheet was calculated with a dynamic explicit FE code PAM-STAMP 2G (ESI co. ltd.). Fig. 7 shows the relationship between the volume fraction of the martensite obtained from EBSD analysis and the effective plastic strain in the draw-bending experiment, together with the result of uniaxial tension experiment. From this figure, we can see that the result of a material element at the mid-plane of the draw-bent sheet is almost identical with one of uniaxial tension. Contrary to this, it should be noted that the evolution of the martensite of a material element at the surface of the draw-bent sheet, with increasing effective plastic strain, is significantly slower than that in uniaxial

tension. In draw-bending, the sheet is subjected to stretch bending-unbending when it is drawn over the die-corner. Therefore, a material element at the sheet surface is subjected to severe tension-to-compression (or compression-to-tension) plastic deformation, but in contrast, a material element at the mid-plane of the sheet is mostly subjected to monotonically increasing tensile strain. Such a difference in deformation mode, between at the surface and the mid-plate, would be the reason why the evolution of martensite is so slow at the surface of the sheet.

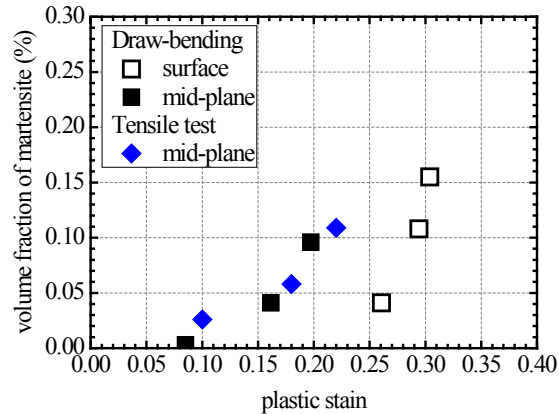


Fig. 7. Evolution of volume fraction of martensite with increasing effective plastic strain under draw-bending and uniaxial tension.

4. Conclusions

Deformation-induced martensitic transformation behavior during draw-bending was investigated on type 304 stainless steel. The present findings are summarized as follows.

- (1) For the hardness distribution in the sheet thickness direction, the hardness at the surface is higher than that at the mid-plate because of the bending effect. The hardness is given as a unique function of the volume fraction of α' -martensite. From this fact, it is concluded that the major mechanism of workhardening of the material is the evolution of the martensitic phase.
- (2) The evolution of the martensite of a material element at the surface of the draw-bent sheet, with increasing effective plastic strain, is significantly slower than that in uniaxial tension, although at the mid-plane it is almost identical with the result in uniaxial tension. This shows that bending-unbending process strongly affects the evolution of martensite. This phenomenon cannot be described by the Olsen-Stringfellow model which assumes that the volume fraction of the martensite is given as a unique function of accumulated plastic strain.

References

- Fukase, Y., Ebato, K., Okubo, N., Murao, S., 1966. On the Anomalous Behavior of Mechanical Properties in Metastable Cr-Ni Austenitic Stainless Steels at Ambient Temperatures. *Journal of the Japan Institute of Metals* 32-1, 38-44.
- Tamura, I., Maki, M., Hato, H., Aburai, K., 1966. On the Plasticity Induced by Martensitic Transformation in Fe-Ni Alloys and Fe-Cr-Ni Alloys. *Journal of the Japan Institute of Metals* 33-12, 1383-1389.
- Ohashi, N., Ono, Y., Nohara, K., 1977. Press Formability of Stainless Steel Sheets. *TETSU-TO-HAGANE*, 63-5, 812-823.
- Hyashi, H., 1977. Sheet Forming of Stainless Steels. *Current Advances in Materials and Processes*, 10, 1185-1188.
- Sumitomo, H., Arakawa, M., Sawatani, T., Ohoka, T., 1976. Delayed Cracking of Deep-Drawn Cup of Marastable Austenitic Stainless Steel. *Journal of the Japan Society for Technology of Plasticity SOSEI-TO-KAKO*, 17-11, 891-898.
- Olson, G. B., Cohen, M., 1975. Kinetics of Strain-Induced Martensitic Nucleation. *Metallurgical Transactions A*, 6A, 791-795.
- Stringfellow, R.G., Parks, D. M., Olson, G. B., 1992. A Constitutive Model for Transformation Plasticity Accompanying Strain-induced Martensitic Transformations in Metastable Austenitic Steels. *Acta Metallurgica et Materialia*, 40-7, 1703-1716.
- Sanga, M., Yukawa, N., Ishikawa, T., 1998. Influence of Deformation Conditions on Deformation-Induced Martensitic Transformation in Austenitic Stainless Steel. *Journal of the Japan Society for Technology of Plasticity SOSEI-TO-KAKO*, 39-1, 72-76.
- Hamasai, H., Ishimaru, E., Yoshida, F., 2014. Cyclic Stress-Strain Response and Martensitic Transformation Behavior for Type 304 Stainless steel. *Applied Mechanics and Materials*, 510, 114-117.